Renewable and Sustainable Energy Reviews 15 (2011) 876–880

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of solar dryers with latent heat storage systems for agricultural products

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ARTICLE INFO

Article history:
Received 15 May 2010
Accepted 2 September 2010

Keywords:
Solar dryer
Latent heat storage systems
Phase change material
Solar energy

ABSTRACT

Drying of agricultural food products is one of the most attractive and cost-effective application of solar energy as it becomes a potentially viable substitute for fuel–wood in much of the developing world. The intermittent nature of the solar energy, which is the main source of energy in solar drying, is indeed one of the major shortcomings of the solar drying system can be alleviated by storing excess energy during the peak time and use it in off sun hours or when the energy availability is inadequate. Developing efficient and inexpensive energy storage devices in solar dryers is as important as developing new sources of energy and reduce the time between energy supply and energy demand, thereby playing a vital role in energy conservation. It improves the energy systems by smoothening the output and thus increasing the reliability. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar drying system incorporating with phase change materials (PCMs) for drying agricultural food products.

Contents

1. Introduction

Drying is an important post handling process of agricultural produce which can extend shelf life, improve quality, minimize losses during storage and lower transportation costs since most of the water are taken out from the product during this process [1]. Drying under controlled conditions of temperature and humidity helps the agricultural products to dry reasonably rapidly to safe moisture content and to ensure superior quality of the product [2]. Controlled drying is practiced mostly in industrial drying processes which uses large quantities of fossil fuels. The potential of using solar energy in the agricultural sector has increased due to fluctuation in the price of fossil fuel, environmental concerns and expected depletion of conventional fossil fuels. Solar assisted drying system is one of the most attractive and promising applications of solar energy systems in tropical and subtropical countries. Traditional open sun drying practiced on a large scale in the rural areas of the developing countries suffers from high product losses due to inadequate drying, fungal growth, encroachment of insects, birds and rodents, etc. Properly designed solar dryers may provide a much-needed appropriate alternative for drying of some of the agricultural products in developing countries [3–7]. The intermittent nature of the solar energy, which is the main source of energy in solar drying, is indeed one of the major shortcomings of the solar drying system can be alleviated by storing excess energy during the peak time and use it in off sun hours or when the energy availability is inadequate [8].

There are numerous technologies for storing solar energy in various forms including mechanical, electrical and thermal energy [9]. Thermal energy can be stored in well-insulated fluids or solids as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these. An overview of major technique of storage of solar thermal energy is shown in Fig. 1 [10]. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid, utilizing the heat capacity and change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material. Generally water appears to be the best SHS materials available because it is

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doi:10.1016/j.rser.2010.09.006

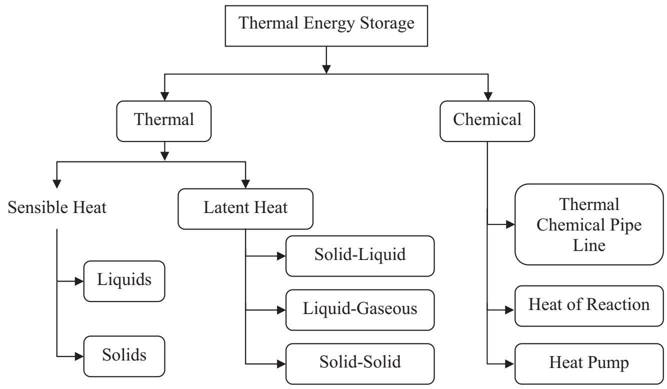

Fig. 1. Different types of thermal storage of solar energy (Bal et al. [10]).

inexpensive and has a high specific heat. However molten salts, oils and liquid metals, etc. are used above 100 °C. Rock bed type storage materials are used for air heating applications. Latent heat storage (LHS) is the heat absorption or release when a storage material undergoes a change of phase from solid to liquid or liquid to gas or vice versa at more or less constant temperature. Thermo-chemical systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material, the endothermic heat of reaction, and the extent of conversion [11]. Amongst above thermal heat storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide high-energy storage density per unit mass and per unit volume in a more or less isothermal process, i.e. store heat at constant temperature corresponding to the phase transition temperature of phase change material (PCM).

The disadvantages of sensible heat storage systems posses the following: (i) low heat storage capacity per unit volume of the storage medium and (ii) non-isothermal behavior during heat storage (charging) and heat release (discharging) processes. On the other hand, LHS, with solid–liquid phase change, has received considerable attention in solar systems due to the follow advantages:

(i) It involves PCMs that have high latent heat storage capacity.
(ii) The PCMs melt and solidify at a nearly constant temperature.
(iii) A small volume is required for a latent heat storage system, thereby the heat losses from the system maintains in a reasonable level during the charging and discharging of heat.

A large number of solid–liquid PCMs have been investigated for heating and cooling applications [12–20]. The PCM to be used in the design of any thermal storage systems should pass desirable thermophysical, kinetics and chemical properties which are given in Table 1 [12,20]. The ideal phase change material to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemically inert; non-toxic and in spite of these advantages, the main hurdles in its dissemination are

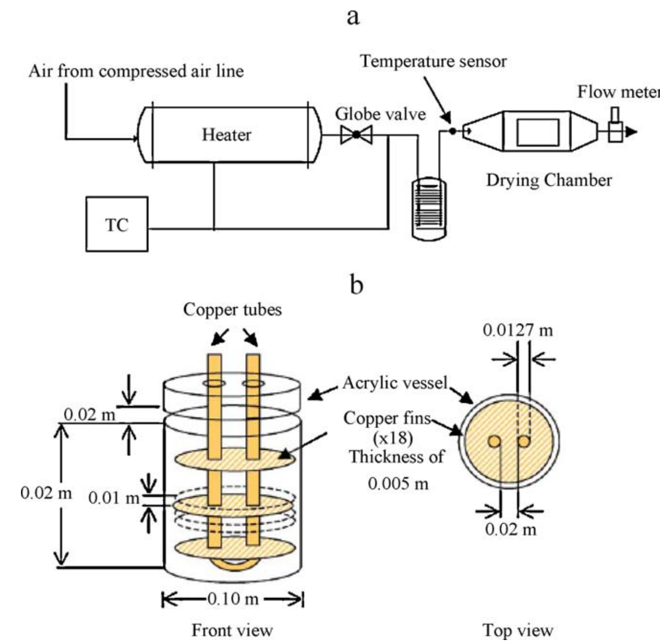

Fig. 2. (a). A schematic diagram of the experiment set-up with attached drying chamber. (b) A detailed sketch of the LHS vessel.

reluctance to acceptance as it is a novel technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues. The growing urban lifestyle also warrants faster drying which is not possible in normal solar dryers [21].

Sharma et al. [22] studied the changes in the melting point, latent heat of fusion and specific heat of PCMs such as stearic acid, acetamide and paraffin wax, both laboratory-grade and commercial-grade, after a repeated number of melting/freezing cycles. Stearic acid melted over a range of temperatures but was thermally stable. Acetamide and paraffin wax showed reasonably good stability throughout 300 melting/freezing cycles and could be considered as promising PCMs. Acetamide absorbed moisture from surrounding, however. As mentioned by Abhat [12], paraffins qualify as energy storage materials due to their availability in a large temperature range and high heat of fusion. Furthermore, paraffins are known to freeze without any supercooling. A major drawback of paraffins is the low thermal conductivity. This problem is addressed through an increase of the surface area of heat transfer between the heat transfer fluid (HTF) and the PCM. The development of a latent heat storage system involves an understanding of heat exchanger and thermal storage material. Therefore efforts have been focused on the development of the heat exchanger configurations such as shell-and-tube, double pipe, plate or spherical shells and also on phase change materials. The use of finned tubes as well as metal fiber and metal matrix, for example, resulted in an increase of 1- to 5-fold of the effective thermal conductivity of the PCM and hence the rate of heat transfer [23]. Esen et al. [24] studied an energy storage and

Table 1
Main desirable properties of phase change materials.

Thermal properties	Physical properties	Kinetic properties	Chemical properties	Economics
Suitable phase-transition temperature	Favorable phase equilibrium	No supercooling	Long-term chemical stability	Abundant
High latent heat of transition	High density	Sufficient crystallization rate	Compatibility with materials of construction	Available
Good heat transfer	Small volume change		No toxicity	Cost effective
	Low vapor pressure		No fire hazard	

release in shell-and-tube heat exchanger units. The results indicated that a shorter energy storage and release time upon charging and discharging the PCM existed on the shell side. Choi and Kim [25] investigated some approaches to augment heat transfer within an LHS by the use of finned tubes and concluded that finned tubes increased the effective thermal conductivity of the phase change material due to the high thermal conductivity of the metal fins which are similar to those reported by Lacroix [26]. Wadekar [27] found that the charge and discharge times were reduced considerably in the system of plate heat exchanger. However, the use of plate heat exchangers remains to be found only on a limited scale.

Several Researchers investigated the heat transfer characteristics of PCMs in an LHS during melting and solidification [28–33]. Sari and Kaygusuz [34] studied the phase transition time, the phase change temperature and the propagation of the solid–liquid interface in both radial and axial directions as well as the effect of the heat flow rate on the phase change stability of steric acid, which was used as the phase change energy storage material. They found that melting and solidification occurred from an upper and lower point in the axial direction, respectively. In the radial direction melting came about from a point closer to the HTF to a point far away from it, while solidification was observed to be in the opposite direction. On the contrary, Sukhatme [35] and Ettouney et al. [23] reported that during the discharge period PCM first solidified at the heat transfer surface. Furthermore, it was indicated that the temperature of HTF affected the charge and discharge times while the effect of the flow rate of HTF in the

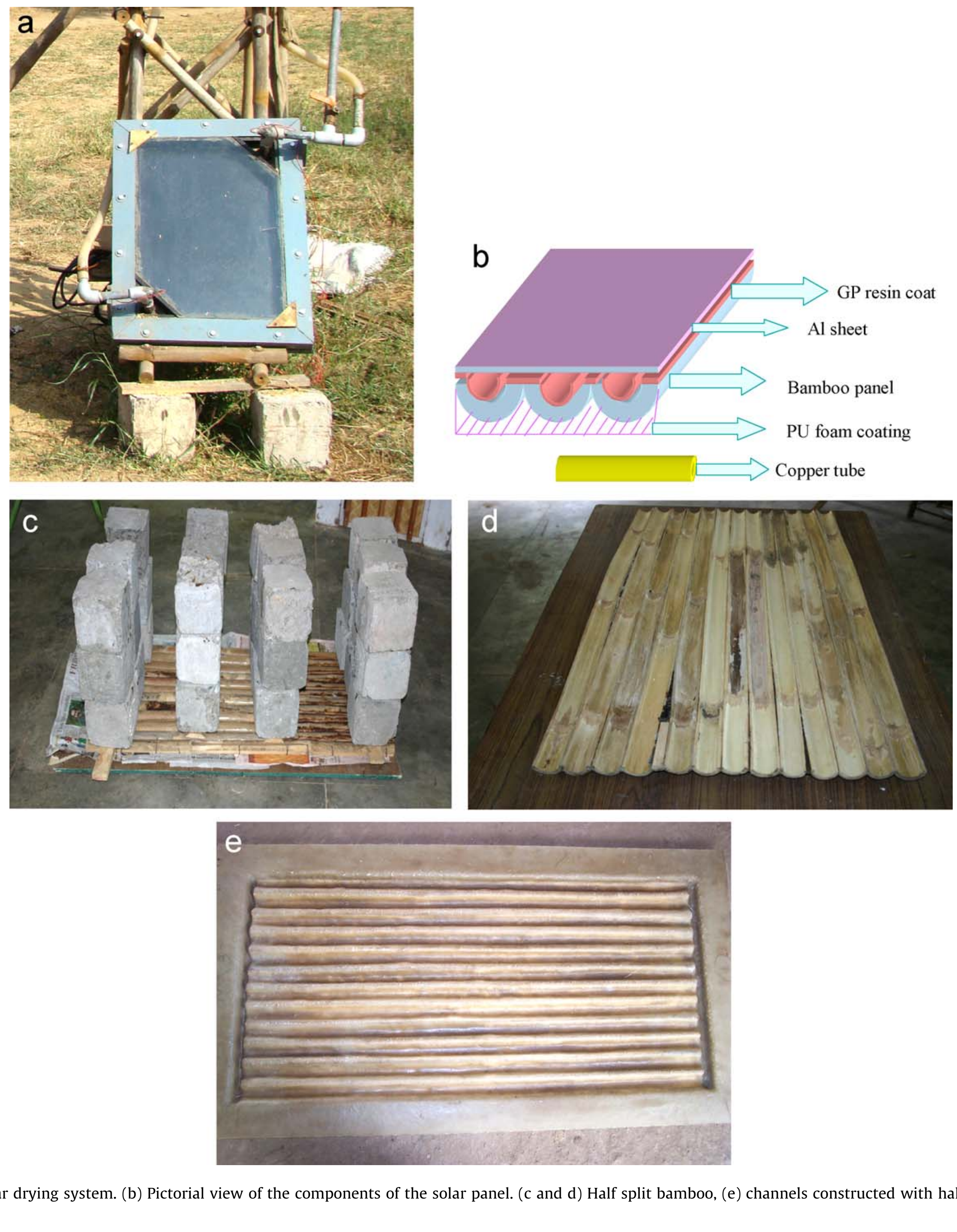

Fig. 3. (a) Solar drying system. (b) Pictorial view of the components of the solar panel. (c and d) Half split bamboo, (e) channels constructed with half split bamboo

laminar flow range did not have any effect on heat transfer in both periods. Similar results were reported by Yanadori and Masuda [36] and Sari and Kaygusuz [34]. However, Ettouney et al. [23] found that the effect of natural convection was negligible in melting process for the case of downward HTF flow and also during a solidification process.

Recently, the incorporation of PCM in solar dryers has grown interest to the researcher. Heat storage system using PCM review article are available for any one application except solar dryers for drying of agricultural food products. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar drying system having latent heat storage with PCMs. This review will help to find the design, development of suitable heat storage unit using PCM for solar specially for agricultural food products.

2. Solar dryers with latent heat storage materials: a review

Very limited information is available regarding the use of latent heat storage to conserve thermal energy during drying. Devahastin et al. [37] proposed, via numerical simulation, the use of latent heat storage to store energy from the exhausted gas of a modified spouted bed grain dryer. A saving of up to 15% could be achieved with the use of such combination. Devahastin and Pitaksuriyarat [38] investigated the feasibility of using latent heat storage (LHS) with paraffin wax (Fig. 2(a and b)) as a phase change material (PCM) to conserve excess solar energy during drying and release it when the energy availability is inadequate or not available and its effect on drying kinetics of a food product (sweet potato). Heat transfer characteristics, temperature profiles as well as the effects of the inlet air temperature and velocity on the charge and discharge periods were investigated. It was found that melting was dominated by heat conduction followed by free convection; melting took place from the center of the LHS to a point far away in the radial direction and took place from top to bottom points in the axial direction. However, only heat conduction was dominant in the solidification process. PCM froze from an outer to an inner of the LHS tank due to heat loss to the surrounding. Charge time decreased with an increase of the inlet air temperature and air velocity. The amount of extractable energy per unit mass flow rate of inlet ambient air was 1920 and 1386 kJ min kg^{-1} when using inlet air velocity of 1 and 2 ms^{-1}, respectively. This LHS could save thermal energy during drying of sweet potato by approximately 40% and 34% when using inlet air velocity of 1 and 2 ms^{-1}, respectively.

Recently, Bal et al. [39] designed and developed a solar dryer with a latent heat storage (LHS) with paraffin wax as a phase change material (PCM) to store excess solar energy during the day time (by using hot air at temperatures close to those exhausted from a typical solar collector) and release it when the solar energy availability is inadequate or not available (by forcing ambient air through the energy storage to extract the stored energy), which implies a possibility of reducing the amount of supplementary energy required in the drying operation and after all continuous drying of agricultural/food products at steady and moderate temperature of 40–75 °C can be possible. Half split bamboo was used in solar dryer to reduce cost as it has good thermal insulation compared to metal and reasonable mechanical strength. Initial measurements of temperature at different points such as inlet, outlet, on black panel and below panel of solar panel with free natural circulation of air and water have been carried out daily. The desired outlet temperature has been achieved for drying of food materials. One main drawback of heat loss in the initial model was rectified by adding a coating of PU foam below the panel. The drying system is shown in Fig. 3(a–e).

3. Conclusions

Efforts of rational and effective energy management, as well as environmental considerations, increase the interest in utilizing renewable energy sources, especially solar energy. Solar energy holds the key to future's non-exhaustive energy source. Because of discrepancy between the energy supply and demand in solar heating applications, thermal energy storage (TES) device has to be used for the most effective utilization of the energy source. This concept of 'solar thermal energy storage using PCM in the solar dryer' reduces the time between energy supply and energy demand, thereby playing a vital role in energy conservation and improves the solar drying energy systems by smoothening the output and thus increasing the reliability for continuous drying of agricultural food products. This paper presents the past and current research in this particular field of latent heat storage in solar dryer for agricultural food products.

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